High-precision torsional magnetometer: Application to two-dimensional electron systems

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A dc torsional magnetometer for use in high magnetic fields is described. With a resolution of 10^{-12} J/T at 5 T and excellent rejection of background moments, this device has been used to study the de Haas–van Alphen effect in two-dimensional electron systems. This resolution is about 100 times that obtained with a commercially available superconducting quantum interference device magnetometer. The device is useful over a wide temperature range including that below 1 K.

In recent years considerable interest has been focused on the physics of two-dimensional (2-D) electron systems[1] at low temperatures. Most of this work has concerned transport properties of the 2-D electron gas and only very recently have the equilibrium thermodynamic properties, such as heat capacity and magnetic susceptibility, begun to be investigated.[2,3] The primary goal of the measurement of these elusive quantities is their direct link, independent of scattering matrix information, to the electronic density of states. The measurement of two-dimensional thermodynamic parameters, however, is made difficult by their tiny magnitude and the invariable presence of background effects which are usually much larger than the sought-for signals themselves. It is the purpose of this paper to describe a torque magnetometer we have developed to measure the low-temperature magnetic susceptibility of 2-D electrons confined at semiconductor heterojunction interfaces. This instrument combines great sensitivity with rejection of isotropic background magnetizations in favor of the intrinsically anisotropic signal arising from the 2-D electrons. While we have applied this device solely to semiconductor heterostructure samples, it should be of general use whenever measurements of small anisotropic moments are required. Although it may be employed over wide ranges of temperature and magnetic field its compatibility with very large fields (in excess of 10 T) and the low temperatures obtained with dilution refrigeration (below 1 K) distinguishes it from other torque magnetometers of more conventional design.[4]

The technique we employ relies on the simple fact that in the presence of an applied magnetic field $\overline{B}$, a magnetic moment $\overline{\mu}$ experiences a torque $\overline{\tau} = \overline{\mu} \times \overline{B}$. For isotropic materials, aside from the effects of depolarizing fields, the induced moment $\overline{\mu}$ is parallel to $\overline{B}$ and thus no torque results. For 2-D electrons, however, the induced orbital moment $\overline{\mu}$ is constrained to be perpendicular to the 2-D plane whose orientation relative to the applied field is arbitrary. A torque measurement therefore selects out the anisotropic component of the magnetization due to the 2-D electrons and does not "see" isotropic background moments arising from the substrate or sample holder.[5] To measure this torque, the sample is mounted on a thin fiber which is stretched perpendicular to the external magnetic field. The sample is oriented so that the normal to the 2-D plane lies at a small angle to the field. With this arrangement, the torque on the magnetized sample twists the fiber and this twist is capacitively detected.

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To make such torque measurements, we have constructed a torsional magnetometer, schematically illustrated in Fig. 1. A fine wire (37-μm-diam, 2-cm-long Pt-W alloy[6]) is held, under tension, between two plastic supports attached to a brass mounting thermally anchored to the mixing chamber of a dilution refrigerator capable of reaching temperatures below 0.1 K. The fiber is perpendicular to the axis of a 9-T superconducting solenoid. Mounted on this fiber is a plastic disk 1 cm in radius whose face is perpendicular to the wire. On one side of the disk a semicircular gold electrode is evaporated which makes electrical contact to the wire. Facing this disk and separated from it by a narrow gap (~ 150 μm) is a plastic plate upon which two pie-shaped electrodes are evaporated. These electrodes are fixed in position, the torsion fiber passing, without touching, through a hole in the plate. These three electrodes are disposed so that two equal capacitances are formed which will vary equally but oppositely as the wire twists.

With the torsion electrode monitored (via the Pt-W wire) by a lock-in amplifier and the two fixed electrodes connected to a ratio transformer, an ac bridge is formed. This circuit is depicted in Fig. 1. The isolated lock-in reference signal drives the bridge and with this arrangement angular resolution at the 10^{-7} rad level is easily obtained. The sample to be investigated is mounted on a thin plastic flat which protrudes from the back of the disk carrying the semicircular electrode. This flat, parallel to the 2-D electron plane, is oriented so that its normal lies at a 15° angle to the magnetic field direction. This angle was chosen to give a nonzero torque and at the same time provide a magnetic field component perpendicular to the sample plane near the maximum obtainable with the magnet.

The actual measurement of the low-temperature mag-

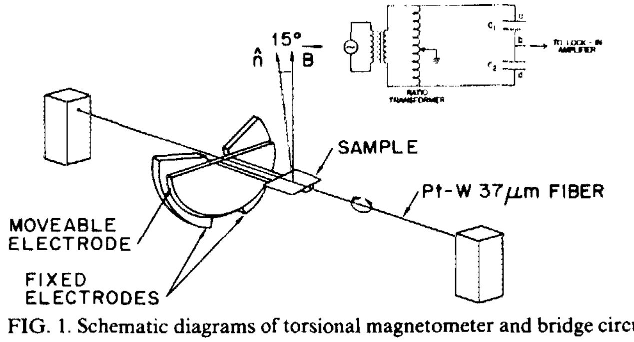

FIG. 1. Schematic diagrams of torsional magnetometer and bridge circuit. The symbol $\hat{n}$ denotes the normal to the 2-D plane. Letters a and d denote the fixed electrodes while letter b denotes the torsion electrode.

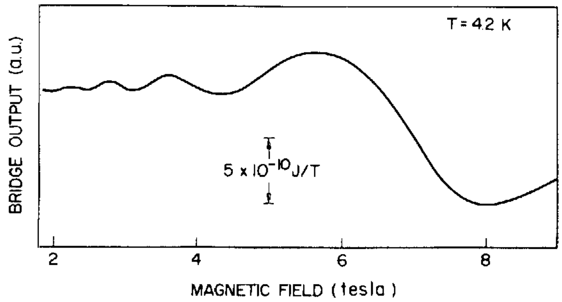

FIG. 2. Raw magnetometer output showing de Haas–van Alphen oscillations in a two-dimensional electron gas. The sample consists of 94 layers of electrons, each with areal density of about 5×10^{11} cm^{-2}, and has a total 2-D area of about 10 cm^2.

netization of the sample consists of simply recording the angle of the torsion bob as a function of magnetic field. Since the device is not used while in torsional oscillation but rather the equilibrium orientation is recorded, it is the dc magnetization that is measured. Such a dc technique has proven essential for the study of 2-D electrons in the quantum Hall regime where long-lived eddy currents can be generated while the system is in the zero resistance state.[7] The magnetic moments associated with these eddy currents can easily overwhelm the thermodynamic magnetization of the sample. Due to the high Q of the torsional oscillations ($Q\sim3.4\times10^4$ at a frequency of 1.6 Hz), it was deemed necessary to quench the oscillations. This is accomplished by a high-purity silver tape which extends around the perimeter of the torsion disk. In a magnetic field, eddy currents in the silver damp the oscillations. The damping, proportional to H^2, gives a Q of about 30 at 1 T.

Calibration of the magnetometer involves several factors. Since the actual angular deflections from equilibrium are quite small ($\sim10^{-4}$ rad), a magnetic moment μ creates a deflection ϕ given by

$$K\phi=\mu B\sin\theta_0, \tag{1}$$

where θ_0 is the angle between $\bar{\mu}$ and the magnetic field $\bar{B}$. In our case $\bar{\mu}$ is parallel (or antiparallel) to the normal to the 2-D plane and θ_0 is set at room temperature to be 15°. Any large changes in θ_0 upon cooling would be seen via the balance point of the capacitance bridge. In practice such large changes do not occur. In Eq. (1), K is the torsion constant of the fiber. This parameter, proportional to the fourth power of the fiber radius, is experimentally determined from the observed torsional oscillation frequency f and the calculated moment of inertia I ($\sim$0.31 g cm^2) via

$$K=4\pi^2f^2I. \tag{2}$$

The final and most difficult aspect of Eq. (1) is the capacitive measurement of the deflection ϕ. The small size of the capacitances, about 3.5 pF, makes stray capacitances important. More significant though is possible nonparallelism of the capacitor gap. Such a defect implies that as the torsion disk rotates, the capacitance changes due not only to changes in the angular overlap of the electrodes, but also because the average gap changes. Given the delicateness of the device, such misalignments are inevitable. We have found it possible, however, to quantitatively estimate their effect on the calibration and find them not to be a serious problem. For a typical device, the final calibration constant is approximately $\Delta\alpha/\Delta\mu=(3.0\times10^4\,\mathrm{J}^{-1})B$, where $\Delta\alpha$ is the change in the balance parameter α, defined as the ratio of one of the capacitances to the sum of both. As expected, the sensitivity increases linearly with the magnetic field. We believe the systematic uncertainty in this calibration to be less than 25%.

The resolution of the magnetometer is approximately 10^{-12} J/T (10^{-9} emu) at 5 T and is limited by vibrations in the cryostat rather than electronic noise. As yet no effort at vibration isolation has been made. It should be emphasized that this mechanical device achieves a precision approximately 50 to 100 times greater than that obtained with a commercial superconducting quantum interference device magnetometer,[8] although the latter device detects isotropic as well as anisotropic moments.[9] By appropriate mechanical isolation, as well as alteration of the capacitor design (narrower gaps, for example), substantially higher resolution may be obtainable.

Our application of this device is to measure the oscillatory magnetization (de Haas–van Alphen effect) of the degenerate 2-D electron gas formed in GaAs/(AlGa)As heterojunctions.[3] The data shown in Fig. 2 reveal the raw output of the capacitance bridge as a function of magnetic field for a superlattice of 94 layers. Analysis of the signal size in such samples has already revealed significant information about the electronic density of states in the sample. We are pursuing these measurements with other more highly homogeneous, higher mobility samples.

To summarize, we have described a highly sensitive, high-field torsional magnetometer for anisotropic systems. With a resolution of 10^{-12} J/T at 5 T, we can study the de Haas–van Alphen effect in 2-D electron systems. It is obvious that the technique can be applied to other systems and, in fact, need not be restricted to low-temperature work.

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[2]E. Gornik, R. Lassnig, H. L. Störmer, W. Seidenbusch, A. C. Gossard, W. Weigmann, and M. v. Ortenberg, to be published in Proceedings of XVII International Conference on the Physics of Semiconductors, San Francisco 1984.
[3]J. P. Eisenstein, H. L. Störmer, V. Narayanamurti, and A. C. Gossard, to be published in Proceedings of XVII International Conference on the Physics of Semiconductors, San Francisco 1984.
[4]For a review of torque magnetometry, see R. F. Pearson in *Experimental Magnetism*, edited by G. M. Kalvius and R. S. Tebble (Wiley, N Y , 1979).
[5]Due to shape anisotropy effects, isotropic moments will in fact, be detected. The torque generated will vary as χ^2, the susceptibility squared. For anisotropic materials, on the other hand, the torque is essentially proportional to χ. Thus, as long as χ is small, isotropic moments are largely rejected.
[6]This alloy was chosen for its tensile strength, electrical conduction, and immediate availability. It may be obtained from Sigmund Cohn Corp., Mt. Vernon, New York.
[7]D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. B **25**, 1405 (1982).
[8]S. H. E. Corporation, San Diego, CA, Model VTS Magnetometer.
[9]Recently T. Haavasoja and D. J. Bishop (unpublished) as well as J. S. Brooks, M. J. Naughton, Y. P. Ma, K. P. Martin, and M. P. Sarachik (Proceedings of the XVII International Conference on Low Temperature Physics, Karlsruhe 1984) have developed mechanical magnetometers with sensitivities comparable to the commercial SQUID mentioned. These devices are sensitive to isotropic moments and therefore cannot discriminate against background effects.